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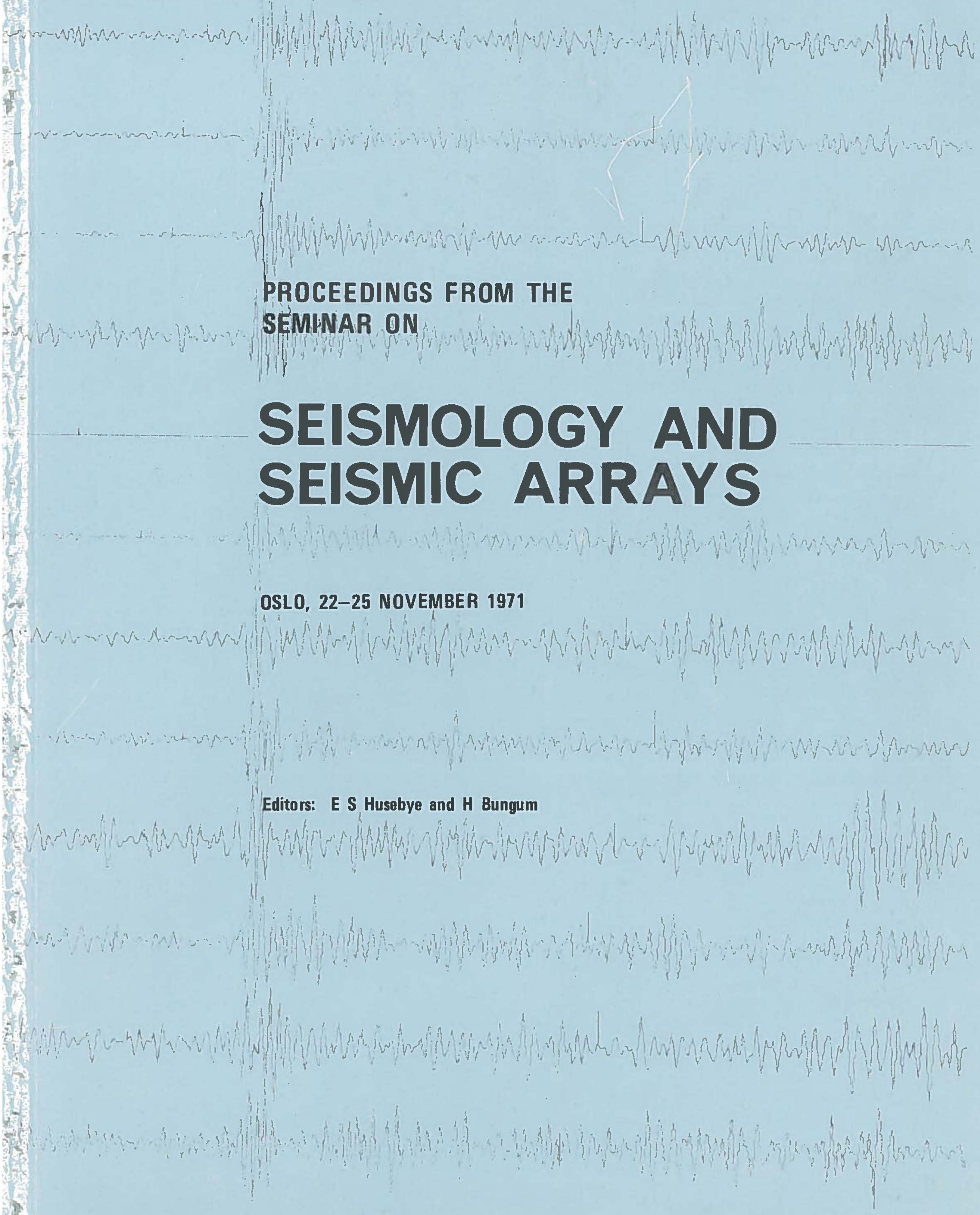

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AN ASSESSMENT OF THE PRESENT SEISMOLOGICAL CAPABILITY FOR THE DETECTION, LOCATION AND IDENTIFICATION OF UNDERGROUND NUCLEAR EXPLOSIONS

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ABSTRACT

A study has been made of the intrinsic capability for the detection, location and identification of underground nuclear explosions of the seismological stations, both standard stations and medium and large aperture arrays, currently deployed throughout the world for a variety of purposes. This general synthesis has then been tested and refined by case studies of the identification of events in both western North-America and in Eurasia. These have demonstrated that in order to make further substantial progress in the low yield range, key studies by the most powerful arrays and the experimental deployment of some improved seismographs and/or more arrays are essential. Data and analyses from the experimental large aperture short and long period arrays such as NORSAR should clarify the discussion and help decide between a number of alternative approaches.

INTRODUCTION

Although the problem of a comprehensive test ban is a political-military security risk problem in which the role of seismology is essentially limited, for some nations the limited capabilities of seismology in any potential non-intrusive verification role are claimed to interact with the security risk problem in a politically important way.

It is important, therefore, to clarify the technical situation with respect to global seismological discrimination, distinguishing between proved deployed capability and projected capability based on a proven technology. For global discrimination capability, the intrinsic capability of the global ensemble of seismological stations, or at least that substantial portion for which records would be made sidered. With this aim of clarification of the technical problems, Resolution 2604 A was adopted at the 1836th Plenary Meeting of the 24th United Nations General Assembly on December 16, 1969. In total, 75 countries made a return to the Secretary General, with 45 of these countries supplying information concerning seismograph stations and arrays from which they would be prepared to supply records on the basis of guaranteed availability.

Using the material supplied in response to Resolution 2604 A, Basham and Whitham (1971) have made a technical assessment of the intrinsic seismological capability for global discrimination contained in these global seismological resources if used to this end. In this paper, the principal elements of this assessment will be summarized, and then updated from both published and modified and relevant unpublished case studies. Projections of currently deployed capabilities will be made. It now seems clear that the power and limitations of the present world-wide deployment of voluntarily cooperating seismic stations has been adequately defined: improvements from such specialized experimental installations as NORSAR, the Very Long Period Experiment of ARPA, and several other developments can now be better assessed as data is collected and analyzed, and case studies published. The assessment of Basham and Whitham (1971) also served to point out the major unsolved problems, and with the additional considerations provided in this paper, illustrates certain key experiments which it is hoped the newer and more powerful research installations will rapidly undertake.

DETECTION AND LOCATION ABILITY WITH THE WORLD-WIDE NETWORK

Basham and Whitham (1971) have described the systematic process of optimization used to reduce 199 short period stations for which information was made available to a conceptual world-wide network of a manageable number of the best short period, vertical-component stations, then used to discuss intrinsic global P-wave detection.

Fig 1 shows the derived 46-station network which includes the 7 short period arrays, together with the location of some 30 additional stations which have short-period magnifications exceeding 50.000 at 1 second. Many of these stations, although not employed in the final detection calculations, are of importance in considering regional studies on discrimination and, in fact, have been used in particular research studies to be outlined later. Most of these additional stations are located in North America and Europe. There is a paucity of high magnification, short-period vertical seismograph stations in the southern hemisphere. To all intents and purposes the power of the 46-station network for P-wave detection is identical to that of the 199-station network feasible, in principle, from the returns.

Fig 2 shows the global contours of the 4-station earthquake P-wave detection threshold defined from this 46-station network. The 4-station P-wave detection threshold is m_b4.0 in southern North America, about m 4.2 throughout much of Eurasia, better than m_b 4.5 for all of the nothern hemisphere, and deteriorating to m_b5.0 in parts of the southern hemisphere. These are theoretical estimates of what *could* be achieved by station data voluntarily supplied within the contest of the UN Resolution.

Fig 3 illustrates the number of stations detecting and the azimuthal coverage of P-waves at an m_b4.5 threshold: in general the network provides detection capability in the northern hemisphere at or below this magnitude.

Location accuracy requires consideration. Such powerful techniques as joint epicentral determination or master event techniques cannot, in general, be utilized, since there has not been adequate cooperation by all nuclear testing powers in releasing publicly the times and positions of suitably large explosions for each test site in order to obtain accurate empirical travel time corrections for each testing area for a network of observing stations. Using some results published by Weichert and Newton (1970), it can be estimated that, with a small network reasonably adequately distributed in azimuth but with no master event control, all events with a nominal focal depth from 0 to about 50 km could be potential surface focus events, or, in this context, potential explosions.

Similarly, advantage cannot be taken, in the general case, of the striking improvement in precision of depth of focus obtainable with an independent estimate of origin time made from time differences between certain seismic phases on the record at a small number of near stations. There are insufficient stations in the network under consideration at distances of 150 to 1000 km from already known test sites. For conceivable test sites, the station distribution is worse.

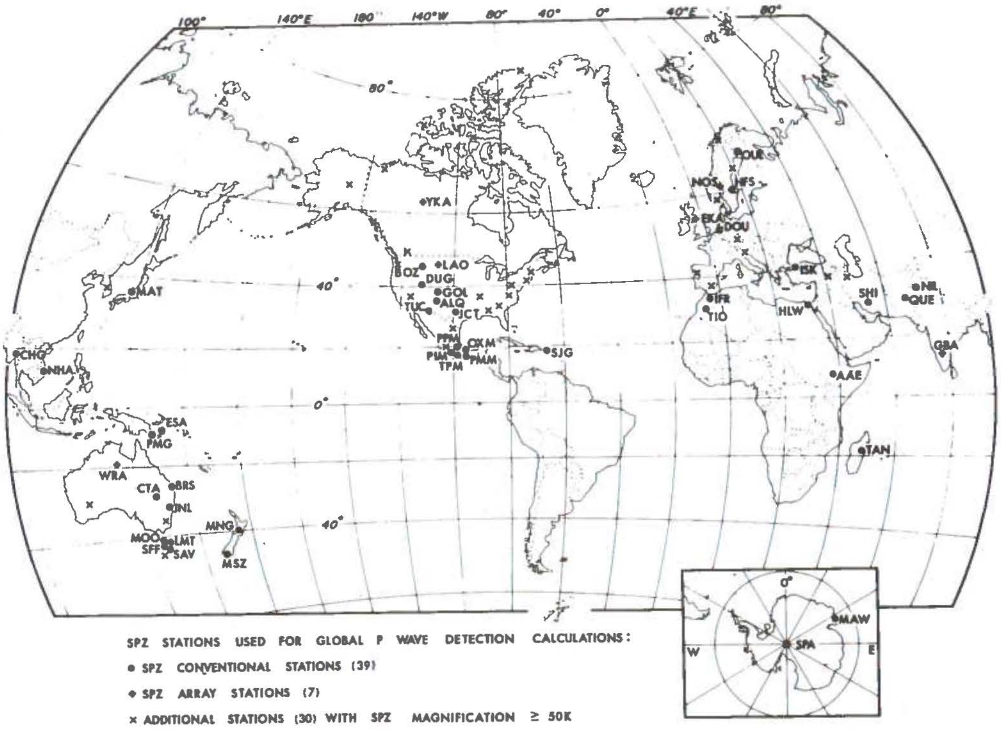

Fig 1. Conventional and array stations in the 46-station SPZ network used for global P-wave detection calculations. The 30 additional stations all have SPZ magnification ≥50 k (from Basham and Whitham, 1971).

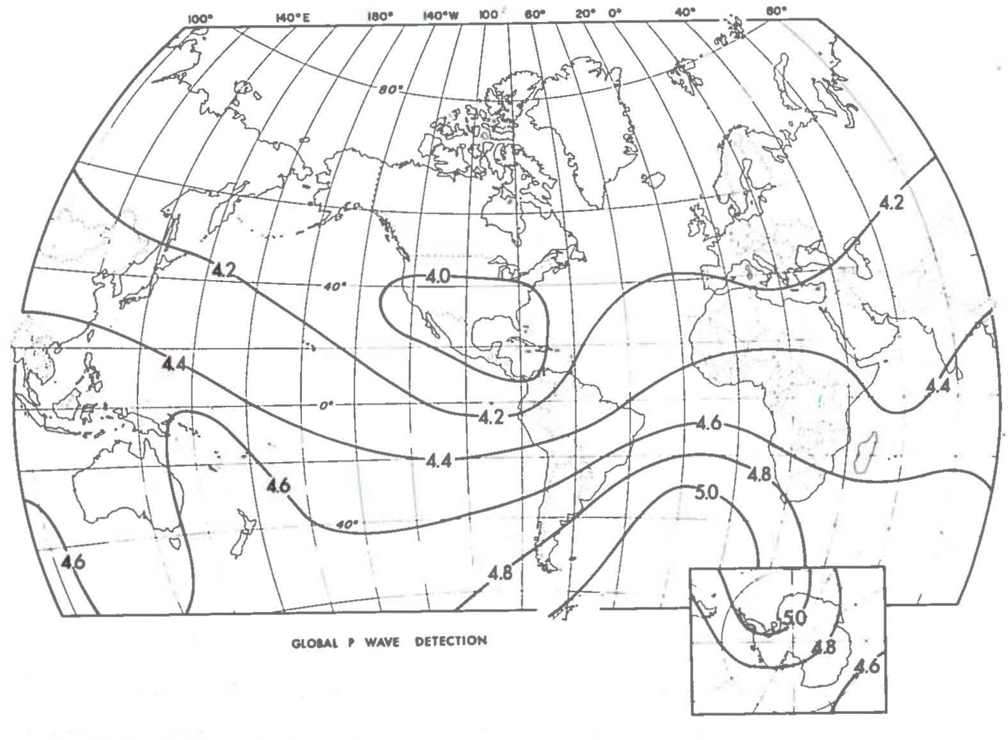

Fig 2. Global contours of the 4-station P-wave detection threshold. A shallow earthquake with this P-wave magnitude will have a 90% probability of detection by ≥4 stations of the 46-station SPZ network (from Basham and Whitham, 1971).

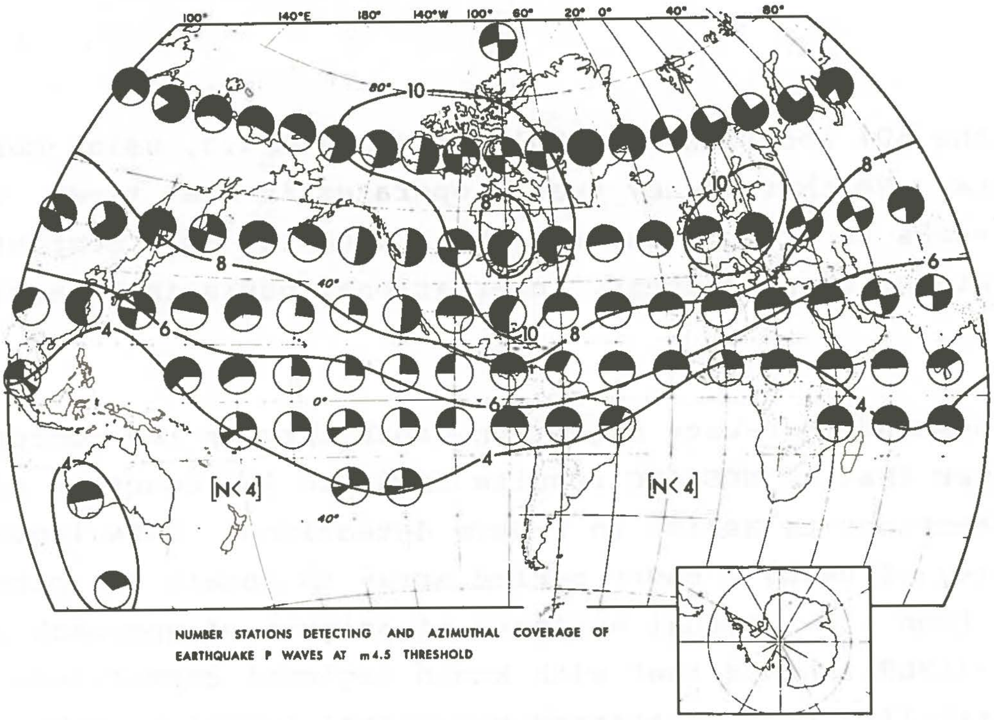

Fig 3. Number of stations detecting and azimuthal coverage provided by the 46-station SPZ network for earthquake P-wave at a threshold m_b4.5 (from Basham and Whitham, 1971).

Accepting an ambiguity of ± 30 km in depth of focus, the approximate location capability can be estimated, both by using the theoretical and practical studies of Evernden (1969) and by examining the actual results obtained from a case study by Weichert and Newton (1970). These results show that errors in epicentral position should be typically 20 to 45 km, with no master control but with data in more than one quadrant and good travel time curves. It is, therefore, concluded that, using the 46-station network, for magnitude 4.5 events at all locations enclosed by the N = 4 contour in Fig 3, epicentral uncertainties should not exceed between 20 and 45 km. Minor exceptions may occur at or near the fringe of the N = 4 contour and at other isolated locations with poor azimuthal coverage. For these exceptions, exact calculations are required to determine the size and shape of the confidence ellipses.

With a slightly better epicentral precision, the magnitude thresholds of events located by the NOS or the ISC operating systems are significantly higher than these results: at about m_b4.5 these agencies have only a 50% probability of detecting and reporting an event, the NOS capability being somewhat worse in parts of Eurasia, but the ISC restoring the 50% location threshold to about m_b4.5, using more complete data. Neither agency system operates in real time: one is several weeks in arrears and the other with the more complete data base furnished on a voluntary international basis is several years in arrears.

The improvement in P-wave detection capability in the conceptual scheme over that of NOS/ISC results from the introduction of the array detections to assist in P-wave detections. This ignores the possibility of using a short period array to obtain an approximate location from its internal estimate of azimuth of approach and $dT/d\Delta$. Weichert (1969) showed that with known regional corrections there is some possibility that multiarray epicentral locations from a small number of arrays might produce, at best, accuracies in location of approximately ± 60 km. The results from any one array, even though well-sited and with a well-calibrated crust, suggest that the general epicentral accuracies which could be obtained are several times worse than this figure. Although there has not yet been an adequate study of the detection and location power of one or two or three arrays working together to assess the situation for low magnitude events, this should obviously be undertaken on an experimental basis as soon as possible.

In summary, retaining the 90% increment concept for all estimates, the present NOS/ISC capability is about m_b4.7 in the northern hemisphere; the power of the conceptual network outlined above brings this down to m_b4.5 by employing the arrays for improved detection; the large aperture arrays alone might reasonably be expected to achieve m_b4.0, but with a poorer location accuracy. However, it appears premature to emphasize a m_b4.0 limit which it remains to be shown is routinely achievable. It is highly desirable to have an adequate case study of events, at least in the critical regions of interest, down to about m_b4.2 with 90% incremental capability. This should be achieved with reasonable location accuracy by merging the medium aperture arrays and good single stations with the large aperture arrays.

RAYLEIGH WAVE DETECTION ABILITY WITH THE WORLD-WIDE NETWORK

A similar analysis of the Rayleigh wave detection capability has been presented by Basham and Whitham (1971). In this study there was some difficulty in deciding upon the interval detection capability for each array, and so the capabilities assumed for individual arrays were deduced using inhouse experience for the tripartite system at Yellowknife and the information, published largely by Lincoln Laboratories, on LASA capabilities. In particular, NORSAR assumptions need verification with operating experience and case-studies on different data samples.

The conceptual long period network so derived consists of some 51 stations. They are shown in Fig 4: 46 stations are conventional and 5 are long-period arrays. In addition, the figure shows 55 additional stations with long period magnifications exceeding 1000. Fig 5 shown the global contours of 4-station Rayleigh wave detection in terms of M_s. This conceptual long period network has the intrinsic capability of M_s3.7 detection in most of North America and western Europe, M_s4.0 for most of the northern hemisphere land masses, and deteriorates to M_s5.6 in parts of the southern hemisphere. Fig 6 shows the number of stations detecting Rayleigh waves and the azimuthal coverage provided at M_s4.0.

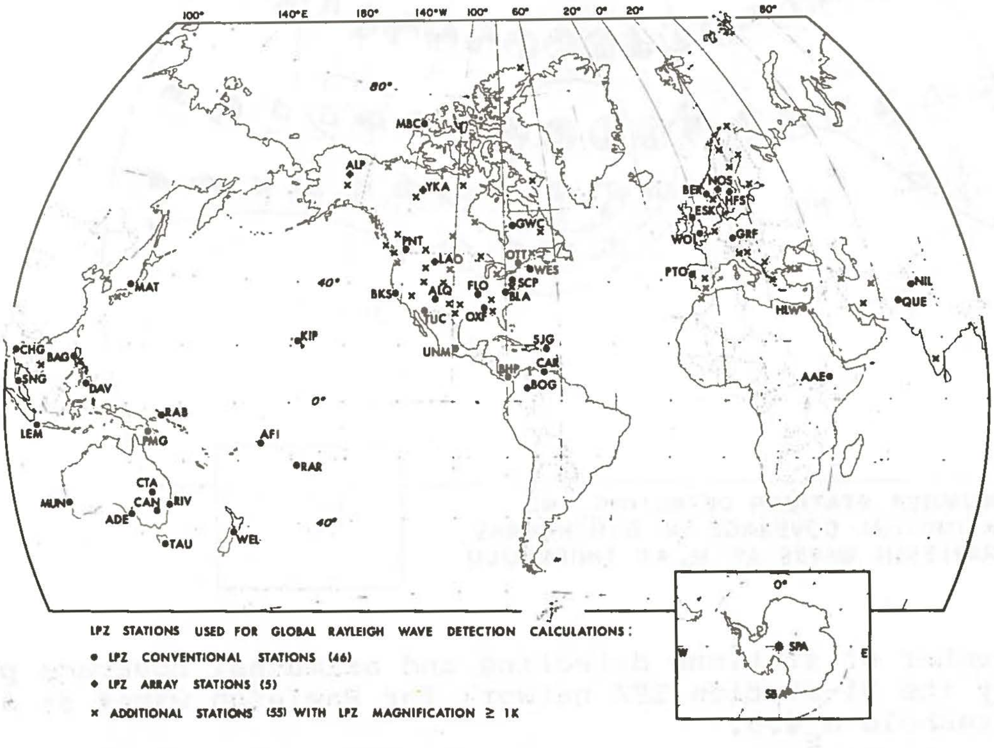

Fig 4. Conventional and array stations in the 51-station LPZ network used for global Rayleigh-wave detection calculations. The 55 additional stations all have LPZ magnifications ≥1 k. (from Basham and Whitham, 1971).

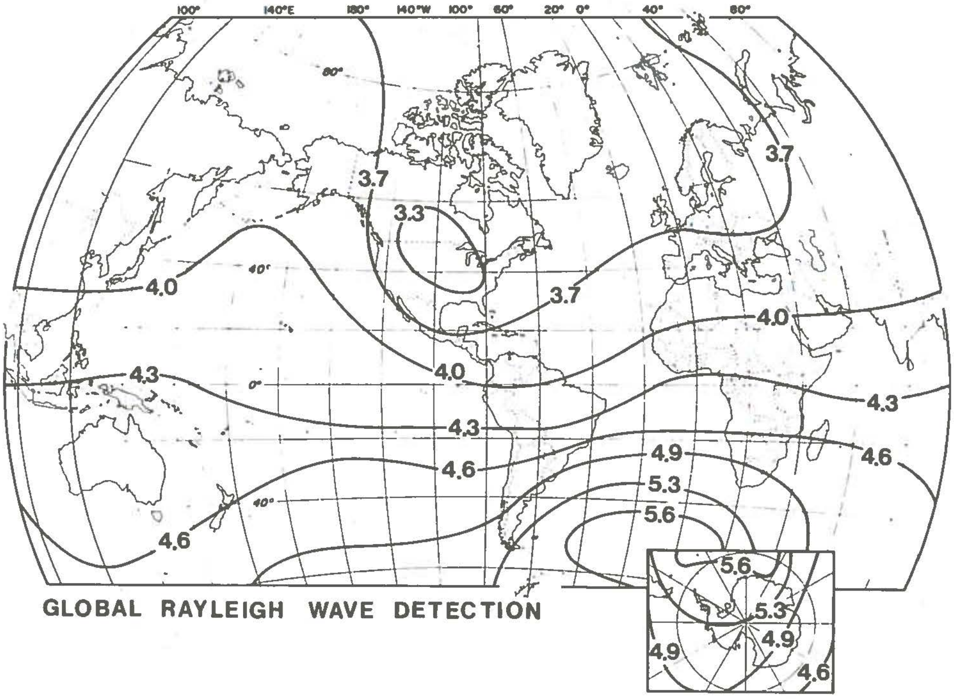

Fig 5. Global contours of the 4-station Rayleigh-wave detection threshold. A shallow earthquake with this M_s magnitude will have a 90% probability of Rayleigh-wave detection by ≥ 4 stations of the 51-station LPZ network.

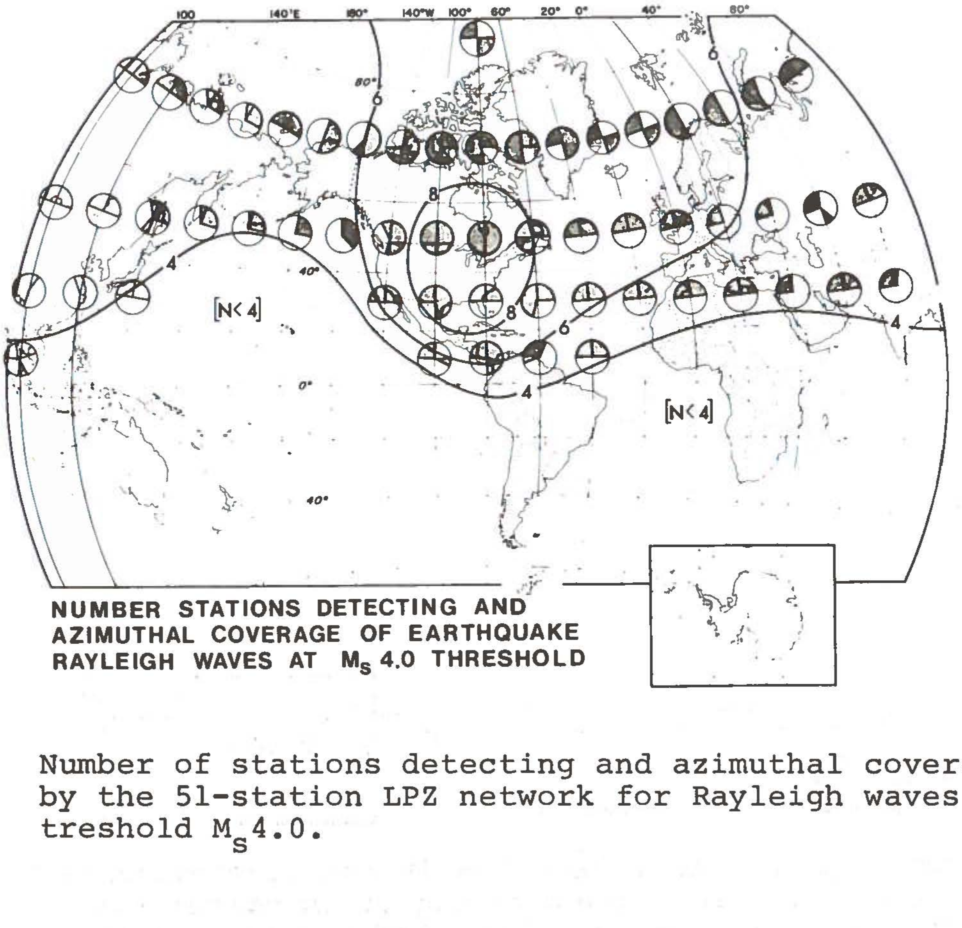

Fig 6. Number of stations detecting and azimuthal coverage provided by the 51-station LPZ network for Rayleigh waves at a treshold M_s4.0.

GLOBAL IDENTIFICATION

The best discriminant between earthquakes and underground explosions is undoubtedly depth of focus. However, at the limit of the detection capability of any network, unless the phases pP and/or sP can be unequivocally identified, as explained earlier all shallow-focus events (say 0 to 50 km) must be accepted as potential explosions.

In this case, the best demonstrated criterion for discrimination is the one involving the relative excitation of P and Rayleigh waves. The threshold of useful application is lower when considered in M_s versus m_b magnitude terms than when more sophisticated spectral approaches are used. Thus, although the latter are certainly useful, in this article the method is dominantly evaluated in terms of the magnitude approach.

GLOBAL IDENTIFICATION - M_s VERSUS m_b STUDIES

A very brief and oversimplified summary of the results and conclusions of Basham and Whitham (1971) is that the global system of stations produces proven detection, location and identification of underground nuclear explosions down to yields of about 60 kilotons in hardrock in most of the northern hemisphere. The threshold was found to be around 20 kilotons in hardrock for a test site in the USA, but it was uncertain, or at least unproved, whether this lower threshold could be reached on a global basis with this ensemble of stations.

The analysis demonstrated a rather unwieldy dependence on M_s versus m_b relationships employed for earthquakes and explosions. Because of this and a number of known and suspected regional variations which could not be included in a global conceptual study, Basham and Whitham (1971) regarded their conclusions as conservative. It was clear that some aspects of a surface-wave magnitude, such as the period of the wave used, maximum amplitude or the 20-second wave, the distance dependence at distances to about 20°, required re-examination and clarification if better global studies were to be undertaken. This viewpoint arose from the earlier work of Basham (1969a, b, c, 1971) which showed that wave propagation effects which depend on the path between an event and a recording station and which can be such a complication in any world-wide assessment, can be turned to great advantage in certain cases. Simply put, a good path can equal the gain obtained from a sophisticated array.

In a recent paper, Marshall and Basham (1972) have re-examined the surface wave magnitude problem in order to obtain surface-wave magnitudes, measured from the maximum amplitude waves at any period within the standard long period pass band, which do not depend upon the geological structure of the path. Their work has defined the first order path propagation effects for continental Eurasia, continental North America, mixed continental/ oceanic, i.e., propagation from Eurasia to North America or vice versa, and purely oceanic paths, that is, propagation from an oceanic source to a coastal station. The path dependent corrections depend upon the period of the surface wave and can be simply applied to the computed surface-wave magnitude. In addition, their study has refined the distance correction term used in a Rayleigh surface-wave computation formula. In their technique, the early practice of Basham is followed and measurements are made of the maximum in the signal independent of its period: for the continental paths these are often at periods of 10-15 seconds and not 20 seconds. Finally, Marshall and Basham (1972) have also devised an approximate correction from the record for focal depth. This work provides a much more direct way of examining the global discrimination problem.

Fig 7 illustrates an M_s versus m_b plot for North American events recorded at Canadian stations using both the previously established and the newly refined formula. The dominant effect of the refined formula is to shift all continental events to lower M_s values. Some idea of the effectiveness of the corrections can be seen from the Aleutian explosions, Longshot and Milrow, which

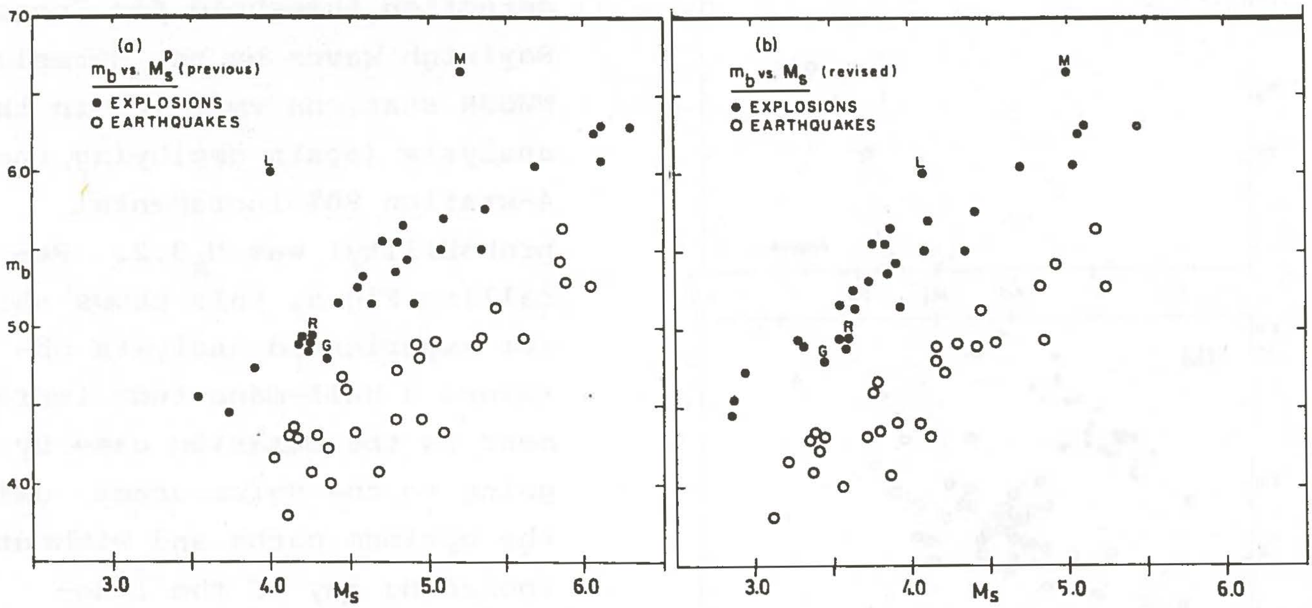

Fig 7. M_s versus m_b observations for North American events recorded on the Canadian standard seismic network (from Marshall and Basham, 1972).

originally fell far to the left of the continental USA explosion trend on the top part of Fig 7 because of the complex path to the Canadian stations, but now agree much better in the lower part of the figure.

A similar study has been made for earthquakes and explosions in the Eurasian land mass by Marshall and Basham (1972). Events which they selected for analysis were 90 shallow focus continental Eurasian or Arctic earthquakes of 1969 and 33 underground explosions in 1968, 1969 and the first half of 1970. All the events in their study had been located by the NOS service, using abstracted seismic readings of P-wave seismic phases from co-operating observatories and institutions throughout much of the world, i.e., in general, the ensemble of stations studied earlier but without P-wave data from the short period arrays considered earlier. Kamchatka and Kurile earthquakes were not included in the sample. Marshall and Basham (1972) obtained very clear discrimination, as can be seen in a regional presentation in Fig 8. Furthermore, the Marshall and Basham data make the

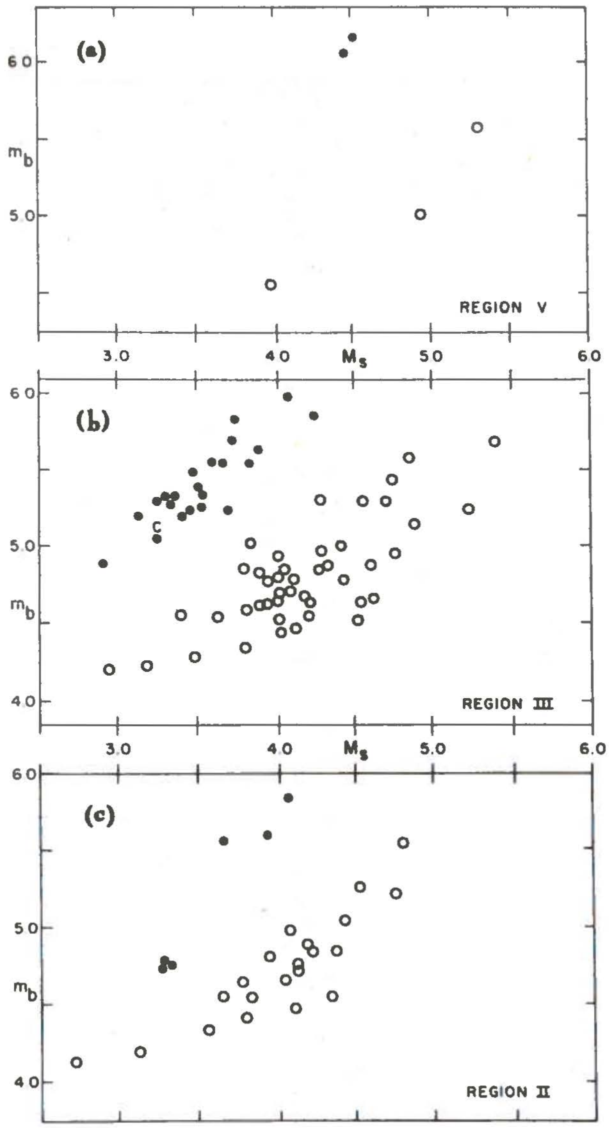

Fig 8. M_s versus m_b observations for Eurasian events recorded on the WWSSN (from Marshall and Basham, 1972).

earthquake population uniform in M_s versus m_b trends for both North America and Eurasia. The detection threshold for Eurasian Rayleigh waves by the Eurasian WWSSN stations employed in the analysis (again employing the 4-station 90% incremental probability) was M_s3.2. Recalling Fig 5, this shows that two experienced analysts obtained a half-magnitude improvement in the Eurasian case by going to the seismograms, using the optimum paths and without including any of the long-period arrays which constituted the theoretical threshold. The reasons for the improvement can be examined in some detail. They include: (1) the dependence of the conceptual study on average M_s versus m_b relationships which are shown to be generally invalid in the regional cases, (2) the path effects which give typical gains in Rayleigh-wave detection of factors of 1.6 in Eurasia and 4 in North America, (3) the fact that skilled analysts can, by visual means, make useful measurements at about half the signal-to-noise ratio used in the world-wide synthesis of Basham and Whitham (1971).

The equivalent case study for North America is now in progress by Basham. However, with the results achieved earlier and related experience with Nevada explosions since that time, the predicted equivalent North American threshold, making use of all available North American standard stations, is M_s2.9.

Using the relationship $M_s = 1.2 \log$ (yield in kilotons) + 1.6, the standard station capability is identification of reported and located events down to about 20 kilotons hardrock yield in Eurasia and about 12 kilotons hardrock yield in continental North America. Also, in these two regions virtually all the events which at present are routinely reported can be identified.

The case studies briefly described appear to have exhausted the capability of the presently installed standard stations of the world. Although virtually all reported events appear to be identified, unreported events represent a major problem. It has been estimated that only around 25% of the total Eurasian earthquakes, for example, for critical areas of Eurasia in the m_b range 4.2 to 4.7, are detected and located by the system operated by NOS using voluntary readings from the world wide network.

The large aperture arrays could produce in the near future a much more extensive data base for the interesting events, as outlined earlier, but the question then arises about progress to lower M_s thresholds.

Fig 9 is a schematic of the two case studies showing the present capability in North America and Eurasia. The heavy shading shows a greater than 90% capability and the light shading the limits of our present data base; the probability of meeting a defined network criterion is falling rapidly in the lightly shaded regions. The data referred to in this schematic is the event information currently available from the United States agency; the 90% levels and the data cutoff limits are significantly different for North America and Eurasia. In general, it can be seen that the explosion identification limits are set by the Rayleigh-wave detection limits, and the number and magnitude of earthquakes available for comparison are set by the P-wave detection and event location limits.

Fig 10 is slightly more generalized, taking one step into the near future with the heavy shading and a more speculative one to the more remote future with the light shading. The heavy shading is limited at m_b4.2 and M_s2.6. The m_b4.2 value is the

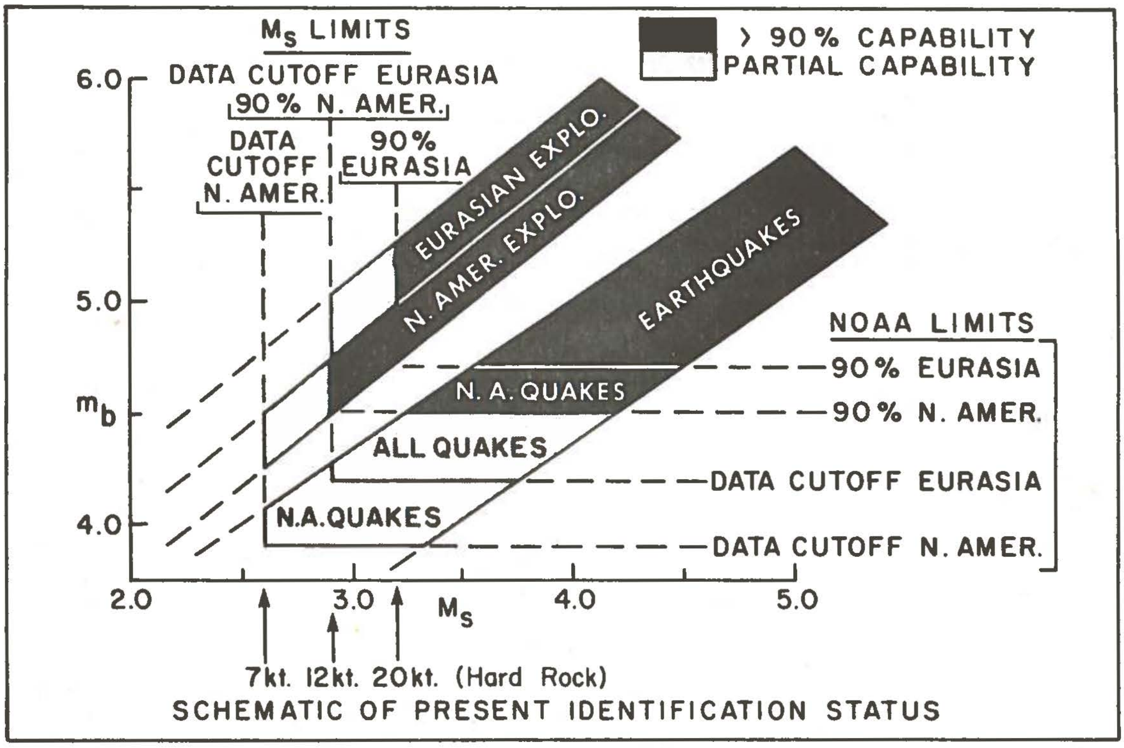

Fig 9. Schematic of present identification status.

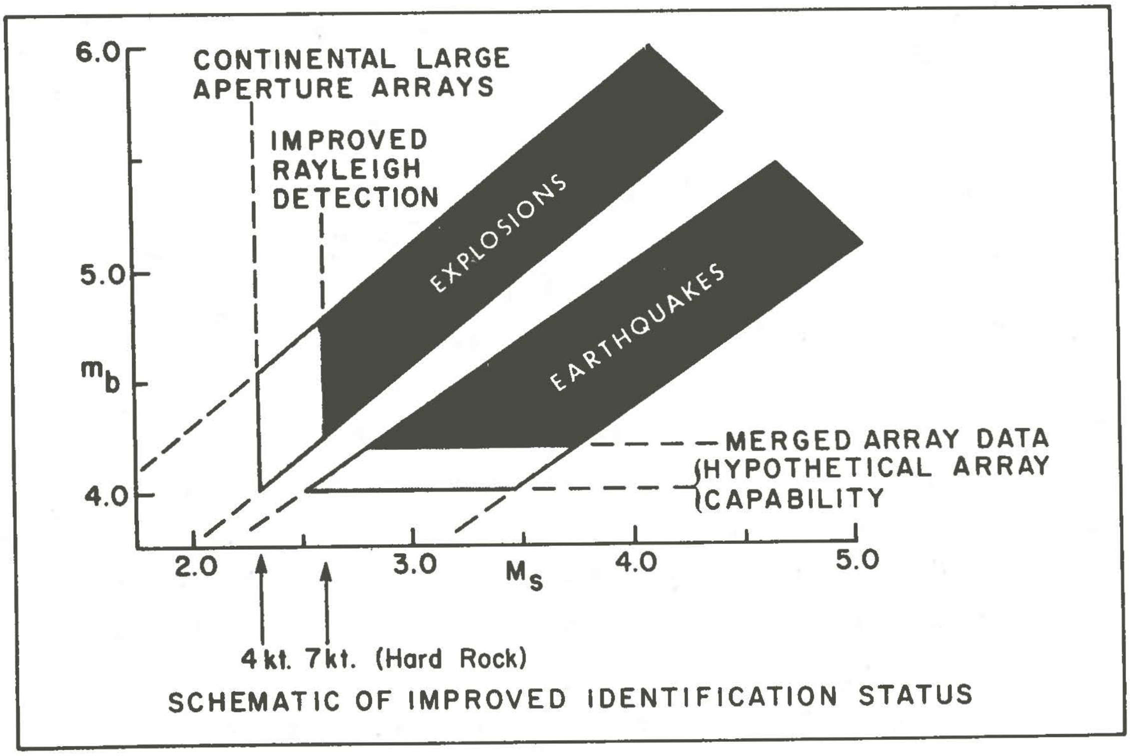

Fig 10. Schematic of potential improved identification status.

one described earlier that can be achieved for general northern hemisphere coverage by the large arrays alone with poor location accuracy, or by adding the medium aperture arrays and some sensitive single stations to produce more accurate epicenters. Basically, seismograph systems currently deployed can achieve this P-wave detection threshold if the appropriate data merging is undertaken. The M_s2.6 limit cannot at present be achieved routinely, or at least this capability has not been clearly demonstrated for all locations in the northern hemisphere. There are a number of existing long period systems that can achieve this detection threshold. These include standard stations at near distances only if the paths are highly efficient for propagation: the only proved example is Canadian and United States standard stations within about 20° of the Nevada Test Site. Alternatively, it can be achieved by single stations at greater distances if they include some signal enhancement processing capability. It can be approached for some regions by the visual output of the very long period stations (Evernden et al, 1971), and it remains to be demonstrated what exactly can be achieved by signal enhancement processing of the digital portion of the eleven very long period systems currently being deployed in world wide locations by the USA. It can, no doubt, be achieved by the large aperture arrays (LASA, ALPA, NORSAR) alone for some regions, but not at a 4-station, 90% incremental probability we have adopted as a requirement.

Although a major case study has not proved the projection, it nevertheless appears likely that intrinsically a routine M_s2.6 capability now exists for many regions. Thus, it is concluded that, if not proven, at least the installed special long period systems will achieve this M_s2.6 threshold and case studies using these facilities to verify these projections are anxiously awaited. If the projection is correct, explosion identification would be achieved in the hardrock yield range of about 7 kilotons.

The lightly shaded area in Fig 10 can at this point in time only be described as hypothetical: it illustrates P and Rayleigh-wave detection that would achieve M_s versus m_b identification of explosions down to about 4 kilotons in hardrock. The P-wave detection threshold is set at m_b4.0, regarded tentatively as the practical limit to be achieved by the large aperture short period arrays and, in fact, probably requiring the construction of additional short period arrays if such a threshold definition is to be achieved globally. The M_s2.3 Rayleigh wave threshold requires large aperture long period arrays sited on the same continents as the regions of interest, good paths, a reasonable gain from master event processing, and again requires additional long period arrays to achieve multi station threshold definition. It is not clear whether M_s2.3 could be routinely achieved, or, indeed, if it is necessary.

The time is thus approaching for intensive studies of the optimum array-special station facilities which can most economically be deployed and integrated for explosion identification at a given yield. This requires the establishment of the optimum combination of P and Rayleigh wave detection thresholds, which is obtained when the M_s and m_b threshold levels converge along the lower locus of the explosion population and the upper locus of the earthquake population. It is estimated for a m_b4.2 threshold the optimum requirement for M_s is about M_s2.8. The potential of existing systems is below this at M_s2.6 and in a Test Ban context there is considerable deterrence for the large block of explosions below this threshold by the negative identification capability, particularly for sites with relatively large m_b values for a given yield, i.e., for events along the upper edge of the explosion population.

If this interpretation of the capabilities of existing systems is correct, it appears that the type of facilities that at present exist can provide clear discrimination of explosions in the 5 to 10 kiloton range in hardrock and in a Test Ban context can provide considerable deterrence to lower levels. There are three important qualifications to this conclusion:

1) the numbers of facilities would need to be increased to provide reasonably uniform coverage at these levels,

2) the required data merging implied by the general capabilities shown on Fig 10 has not yet been attempted in practice and could be a considerable organizational problem,
3) and, because event information is not routinely available at these lower levels, the extrapolation of the earthquake and explosion characteristics remains to be clearly validated by study of the large populations of smaller events.

The hardrock yield estimates shown on Fig 9 and 10 are extrapolations of data available for NTS events on the basis of the M_s values.

OTHER TECHNIQUES OF IDENTIFICATION

Where the spectra of appropriate longer period waves can be measured, very powerful additional discriminants can be used. However, adequate determination of a spectrum requires a higher signal-to-noise ratio than an experienced analyst requires for detecting and measuring a Rayleigh wave in order to compute a magnitude. The Very Long Period Experiment sponsored by ARPA will allow a study of discrimination based on a 40-second surface wave magnitude - greater separation of the populations can be traded off against reduced sensitivity for explosions. However, using the absence of 40-second waves, the key limiting factor will again be the upper locus of the earthquake population. Again, a major data base on earthquakes is required.

Similarly, complexity, Love wave content, the appearance of an impulsive signal on long period seismographs and other characteristics provide methods of considerable use in the classification of events. The problem is that the ones with the soundest theoretical basis such as, for example, first motion studies, the impulsive nature of the long period P arrival, the comparative absence of S waves, are all methods which have a lower limit at teleseismic distances rather close to a body wave magnitude 6, or, in other words, yields of about 100 kilotons in hardrock. Consequently, in the difficult low yield range, these otherwise very powerful methods are inadequate.

There is, perhaps, one exception which is worth a more detailed mention: The P-wave spectral ratio method of identification which has the advantage of potential application from one station alone to a potentially well-defined level. This method depends on the fact that shallow earthquakes tend to have relatively more low frequency energy in the P wave than do explosions of the same body wave magnitude. Results using this type of method are available from studies in the USSR, Japan, USA and Canada. The USA and Canadian methods use digital analyses of array data. The most recent studies of Eurasian explosions using the medium aperture Yellowknife array have indicated that it is possible to combine the earlier concept of complexity in the P-wave coda together with a third moment function describing the frequency content of explosions to obtain a meaningful separation of the Eurasian explosions in the Marshall and Basham sample from the same population of earthquakes. Spectraforming is necessary to maintain the high frequency content of the P signal (Anglin, 1971). The weakness of the method is that noted by many workers. It is very difficult to predict numerically the complexity and, indeed, to obtain exact agreement between theory and practice with respect to the third moment descriptor of the frequency spectrum. A larger data base is necessary to convince the pessimist because of the lack of a generalized theoretical basis for the empirical results, and how can criteria specific to one national station be accepted within a multi-national context. Furthermore, the method requires spectraforming rather than beamforming. It is, therefore, fairly clear that even with noise corrections, a modest signal-to-noise ratio is required in order to obtain a reasonable spectrum and the lower limit of applicability of the method must be perhaps a half magnitude unit higher than the lower detection limit of an array. However, the potential of the method is that, if similar or more sophisticated multivariate techniques can be developed for larger aperture arrays or for cooperating medium aperture arrays, automated P-wave discrimination may be possible down to yields as low as 10 kiloton in hardrock, with a 90% probability of application.

It should, however, be emphasized that the establishment of a short period discriminant either directly dependent on the frequency content or in some multivariant manner between the time and frequency domains, perhaps more complicated than the one recently devised by Anglin (1971), will require once again an adequate low magnitude earthquake data base in the area of interest and a range of low yield explosions, 1-20 kilotons.

UNUSUAL EVENTS

Depending upon the stress drop or its rate, some natural earthquakes may occur which violate the usual M_s versus m_b criteria. It is obviously extremely important to establish where these unusual events occur, their frequency, tectonic pattern, and so on, and understand the reason for them. Similarly, it will be very useful with adequate data bases to study the population statistics of M_s versus m_b in order to assess the deterrence - false alarm rate trade-offs based on adequate sampling of a complex world.

EVASION

This paper has referred throughout to hardrock yields. Decoupling techniques to reduce the seismic signal levels from underground explosions, or deliberate attempts to simulate earthquake signals, or attempts to hide or confuse the seismic signature of explosions in natural earthquake activity are not discussed. Such questions need competent and realistic examination within the political-military-security risk context of a comprehensive test ban discussion: many of the seismological facts are known and agreed, but there appears to be disagreement at the present time on the significance of this class of potential problems.

CONCLUSION

Discrimination is possible in the northern hemisphere down to hardrock yields between 12 and 22 kt, depending upon the test site: the remaining problems at this level relate to the number, location and nature of natural events which may violate $M_s:m_b$ criteria, decoupling, evasion and the lack of an adequate detected and located lower magnitude earthquake base.

Evaluation of array and very long period station capabilities is underway: 7 kt hardrock yields should be reached anywhere in the northern hemisphere. There is a possibility that a 4 kt hardrock yield target could be attained with optimum deployment of present technology. It is not certain if a target of 2 kt in hardrock can be reached globally in any practical scheme.

NORSAR will play an important role in (a) contributing to the low magnitude earthquake base necessary for further progress, including on-line research in P-wave discriminants and (b) providing the automated capability for extensive surface wave-body wave case studies necessary for further progress.

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